

Blunted-Cone Heat Shields of Atmospheric Entry Vehicles

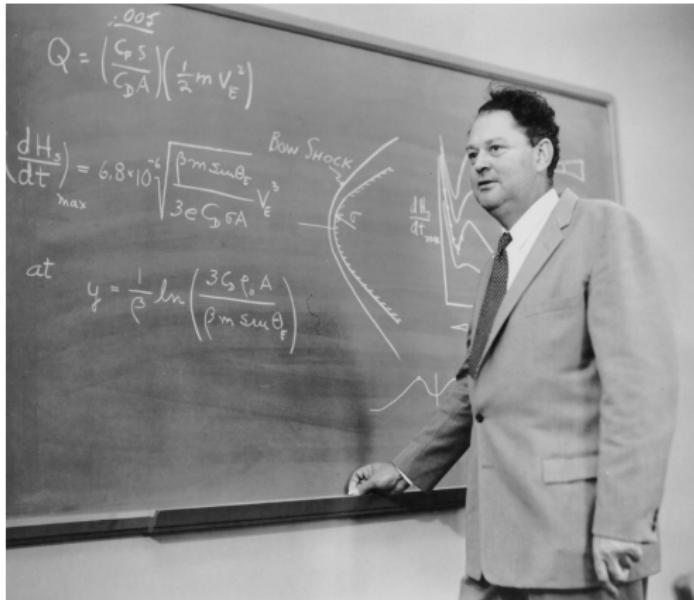
John E. Sader

Eleanor C. Button, Charles R. Lilley, Daniel Ladiges,
Edward Ross and Nicholas S. Mackenzie

Department of Mathematics and Statistics
The University of Melbourne
AUSTRALIA



Blunt Body Vehicles: Allen & Eggers (1953)



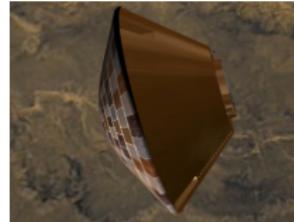
Atmospheric Entry Vehicles: sphere-cone



Galileo
Jupiter, 1995



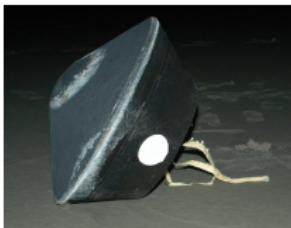
DeepSpace2
Mars, 1999



Beagle2
Mars, 2003



Huygens
Saturn, 2005



Stardust
Wild 2, 2006



MSL
Mars, 2011

Heat Shield Design

“The basic forebody geometry has been kept the same as the original Viking shape to benefit from the... concept of ‘heritage’.”

M. Schoenenberger *et al.*, AIAA Paper 2009-3914 (2009)

Cone angles choices

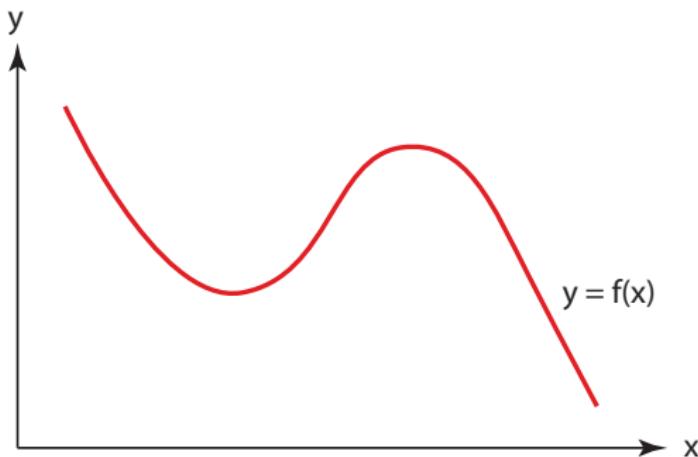
- ▶ Practically they vary from 45 to 70 degrees
- ▶ Packaging, Atmosphere, Heating, Drag, Stability...
- ▶ Larger cone angles: Can decrease dynamic stability, increase drag...

M. Tauber, M. Wright and K. Trumble
“Cone Angle Choices for Atmospheric Entry Vehicles: A Review”
IPPW-6, Atlanta, Georgia (2008).

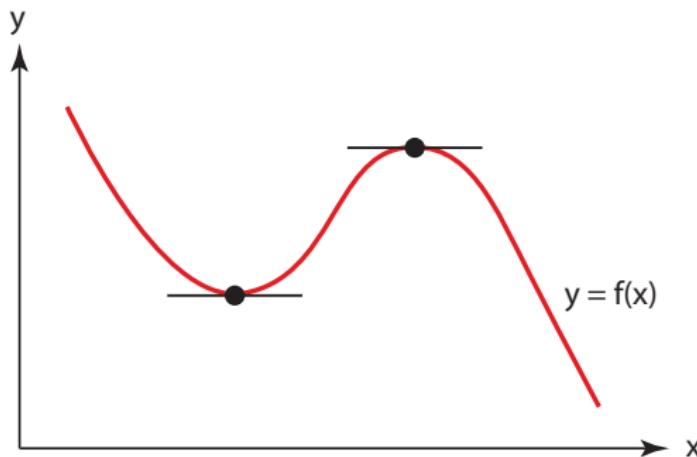
Heat Shield Design - Stability

- ▶ Torque generated by interactions with atmospheric particles is **stabilising**
- ▶ Insensitive to (small) shape changes
- ▶ True for all flow regimes

Calculus of Variations (Intro 1)

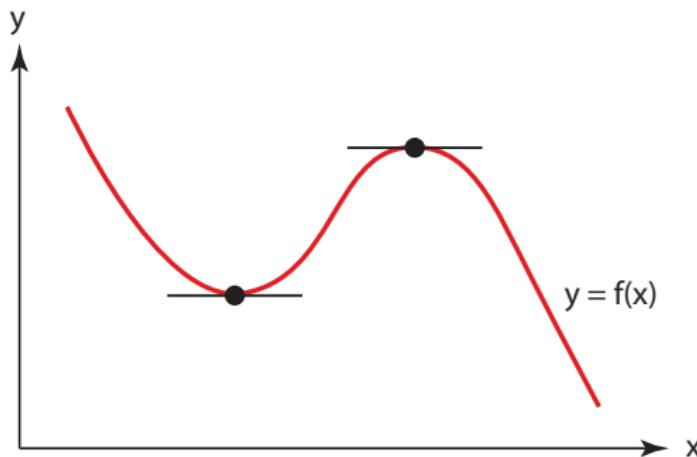


Calculus of Variations (Intro 1)



- ▶ Stationary points: 1st derivative

Calculus of Variations (Intro 1)

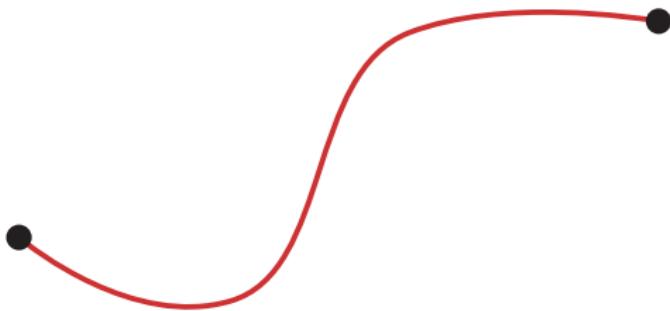


- ▶ Stationary points: 1st derivative
- ▶ Maxima/Minima: 2nd derivative

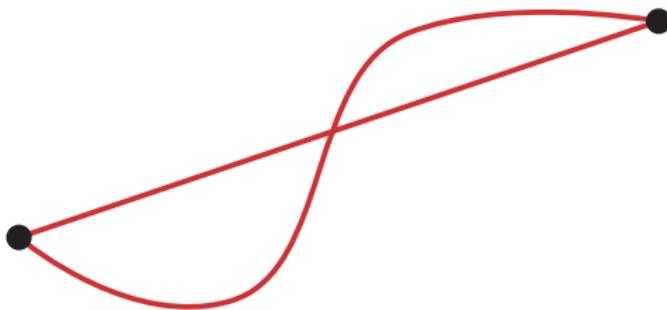
Calculus of Variations (Intro 2)



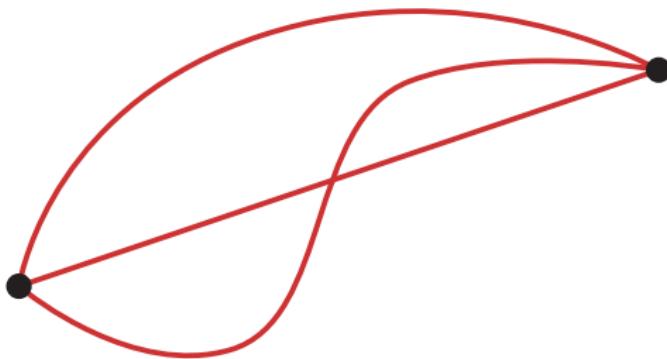
Calculus of Variations (Intro 2)



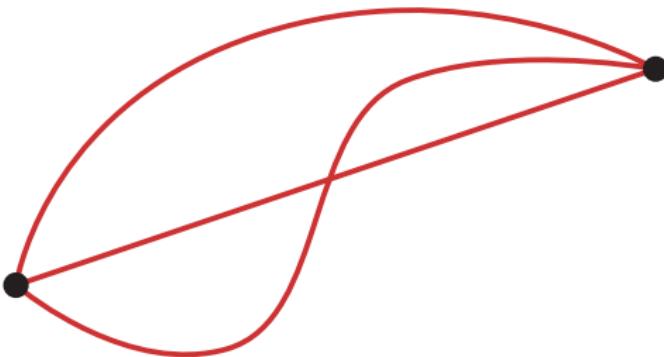
Calculus of Variations (Intro 2)



Calculus of Variations (Intro 2)

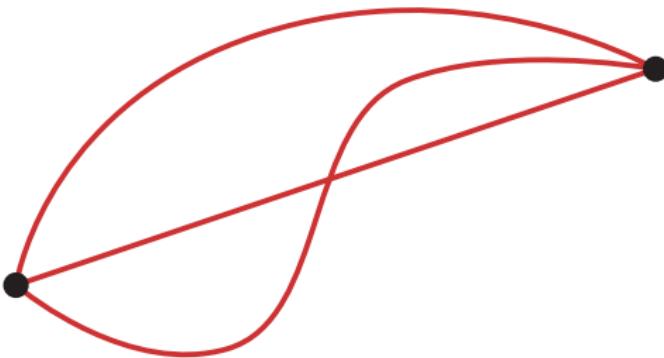


Calculus of Variations (Intro 2)



- ▶ Curve length: $S = \int_{x_0}^{x_1} \sqrt{1 + f'(x)^2} dx$

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Calculus of Variations (Intro 2)

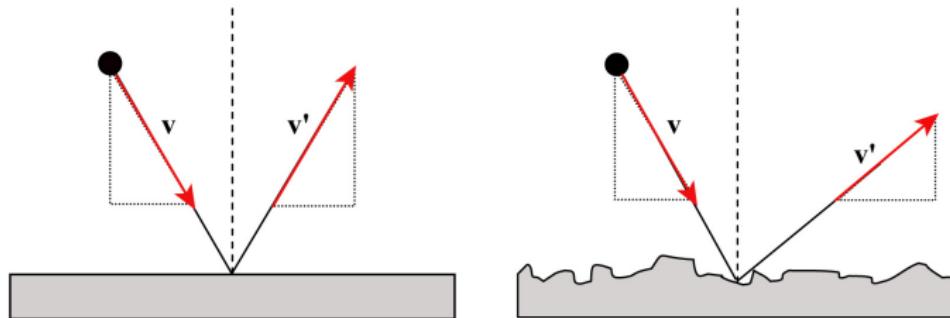


- ▶ Curve length: $S = \int_{x_0}^{x_1} \sqrt{1 + f'(x)^2} dx$
- ▶ 1st derivative \rightarrow *Straight line!*
- ▶ 2nd derivative \rightarrow *Minimum length!*

Flow Models

Free Molecular Flow (Outer Atmosphere)

- ▶ Specular and diffuse reflection
- ▶ η fraction of specular reflection



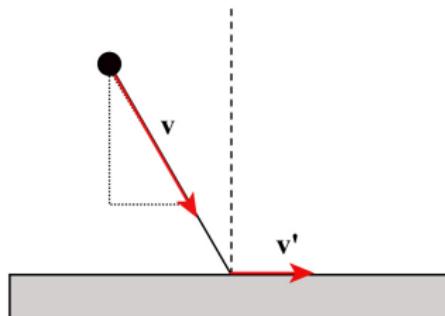
Specular

Diffuse

Flow Models

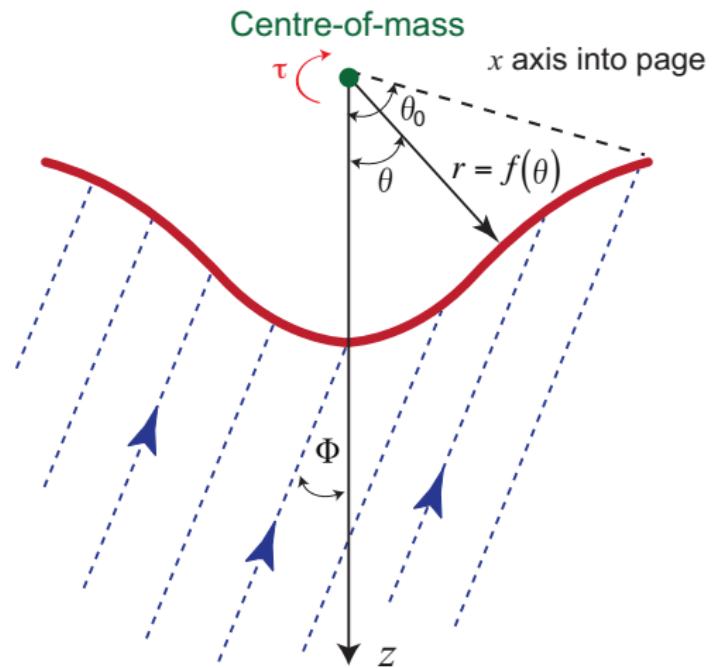
Continuum Flow (Inner Atmosphere)

- ▶ Newtonian impact theory
- ▶ Reasonable for hypersonic flows



Newtonian

Geometry



Torque

► Free Molecular Flow

$$\boldsymbol{\tau} = -\frac{\pi}{2}\rho U^2 \sin(2\Phi) \mathbf{i} \int_0^{\theta_0} \left[(1-\eta)f^2 \sin \theta (\sin \theta F(\theta) + 2 \cos \theta G(\theta)) \right. \\ \left. + \eta \frac{4f^2 f'}{f^2 + f'^2} \sin \theta F(\theta) G(\theta) \right] d\theta$$

► Continuum Flow

$$\boldsymbol{\tau} = -\frac{\pi}{2}\rho U^2 \sin(2\Phi) \mathbf{i} \int_0^{\theta_0} \frac{2f^2 f'}{f^2 + f'^2} \sin \theta F(\theta) G(\theta) d\theta$$

where $F(\theta) = f' \cos \theta - f \sin \theta$ and $G(\theta) = f \cos \theta + f' \sin \theta$

Euler-Lagrange Equation

$$\begin{aligned} & f^6(\sin \theta - 3 \sin 3\theta) + 64ff'^5 \sin^2 \theta \cos \theta \\ & + f'^6(5 \sin \theta - 3 \sin 3\theta) - 4f^5f'(\cos \theta - 3 \cos 3\theta) \\ & + 2f^2f'^3 \sin \theta [f'(5 + 27 \cos 2\theta) - 4f'' \sin 2\theta] \\ & + 8f^5f'' \cos 2\theta \sin \theta + 2f^4f' \sin \theta [f'(3 + 11 \cos 2\theta) \\ & + 12f'' \sin 2\theta] + 4f^3f'^2[f'(3 \cos 3\theta - \cos \theta) \\ & + 3f''(\sin \theta - \sin 3\theta)] = 0 \end{aligned}$$

$$f'(0) = 0$$

$$f(\theta_0) = D$$

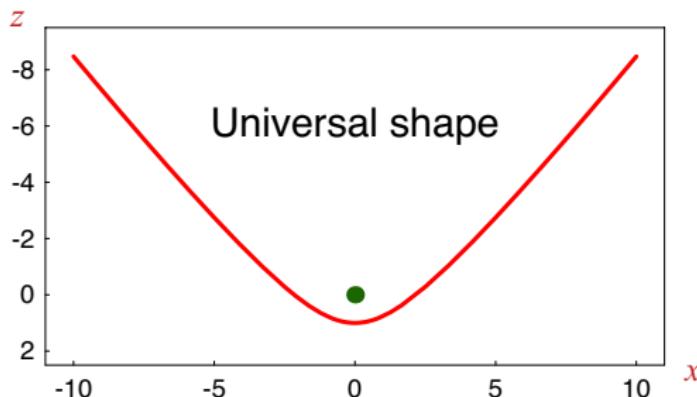
Euler-Lagrange Equation

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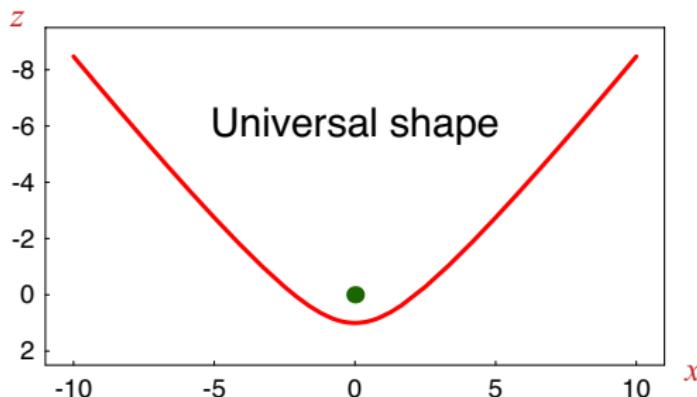
$$f'(0) = 0 \quad f(\theta_0) = D$$

- ▶ Independent of BCs at surface
- ▶ Continuum AND Free Molecular flow

Numerical Solution



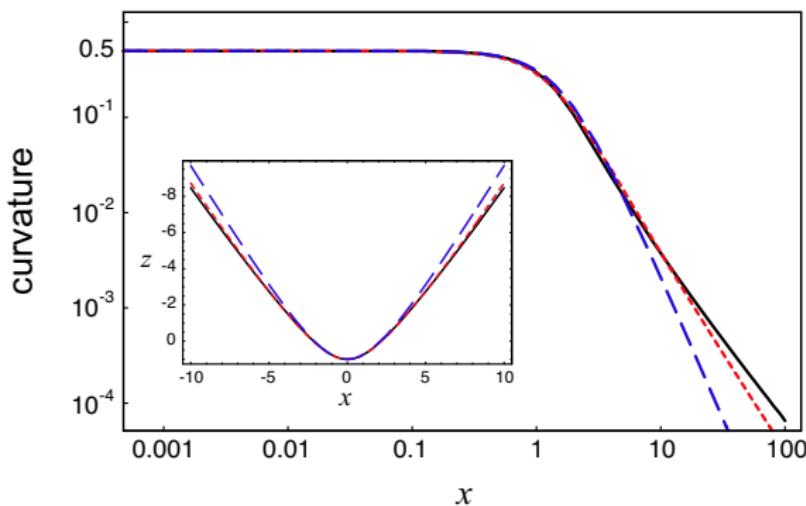
Numerical Solution



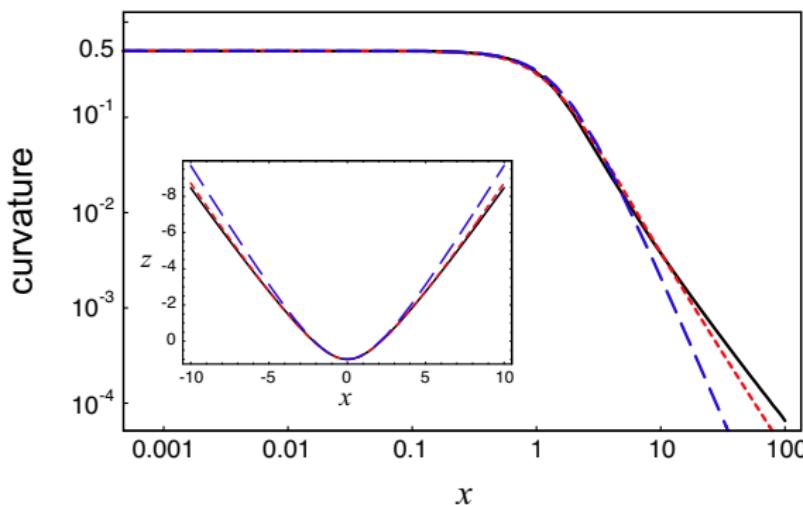
Empirical approximations:

- ▶
$$z = 1 - \frac{2}{\pi^2} [\sqrt{2}\pi x \arctan(\pi x / (4\sqrt{2})) - 4 \log(1 + (\pi^2 x^2 / 32))]$$
- ▶
$$(z - 5)^2 - 2x^2 = 16$$

Curvature of Heat Shield

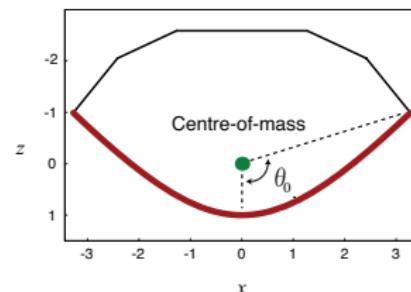
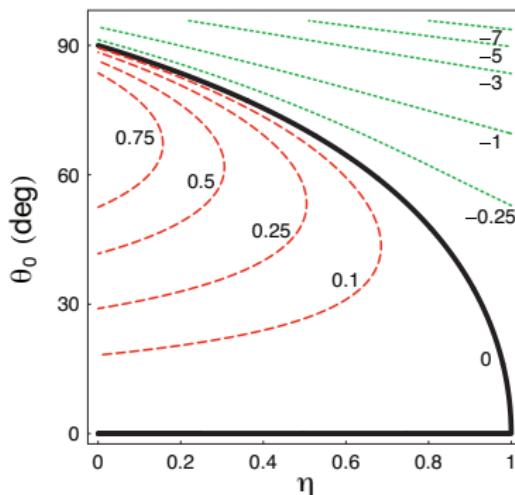


Curvature of Heat Shield

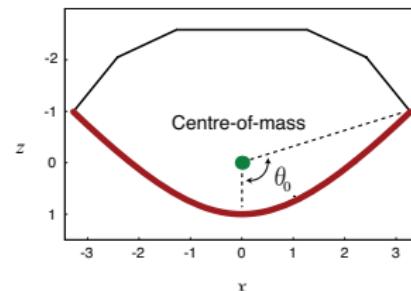
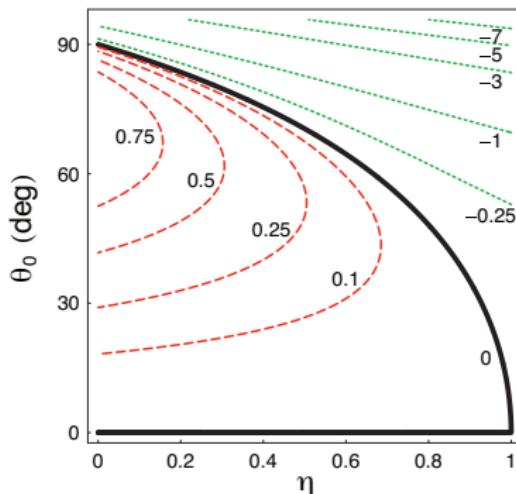


Minor angle of the cone is $\arcsin(1/\sqrt{3})$, so $\theta_0 \approx 144.74$ deg.

Stability for FM flow



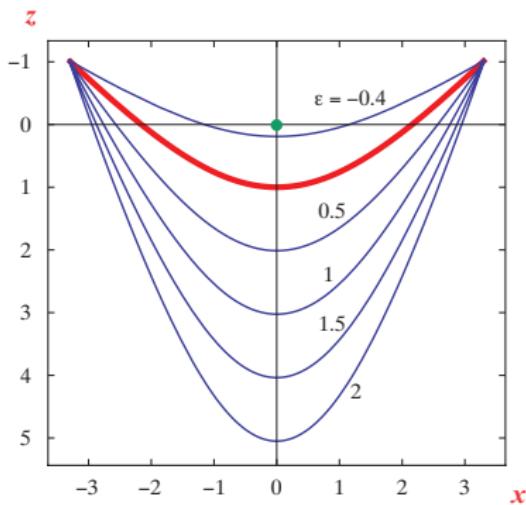
Stability for FM flow



Continuum flow: Always stable!

Perturbations to heatshield shape

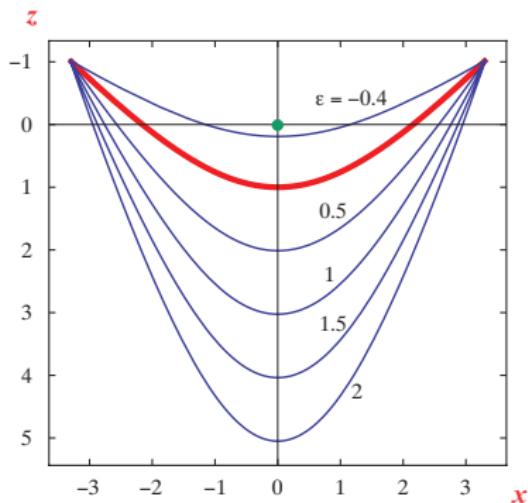
Heatshield



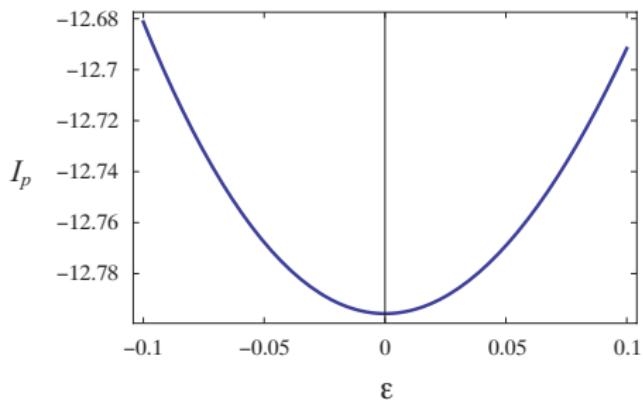
Torque integral (continuum)

Perturbations to heatshield shape

Heatshield

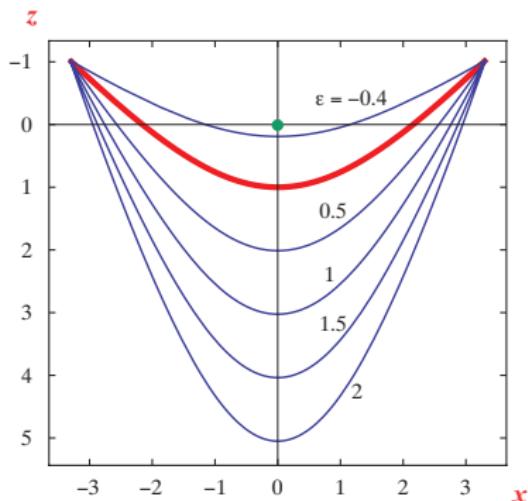


Torque integral (continuum)

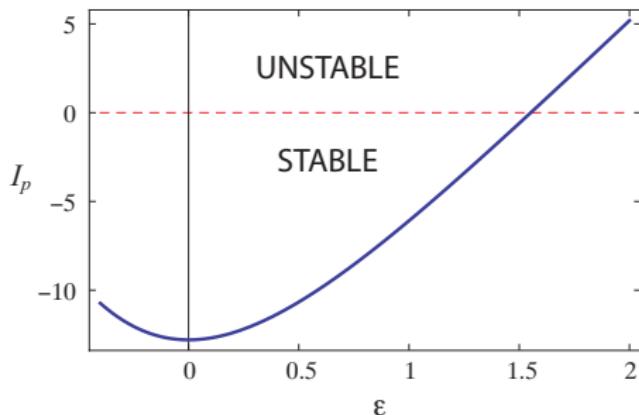


Perturbations to heatshield shape

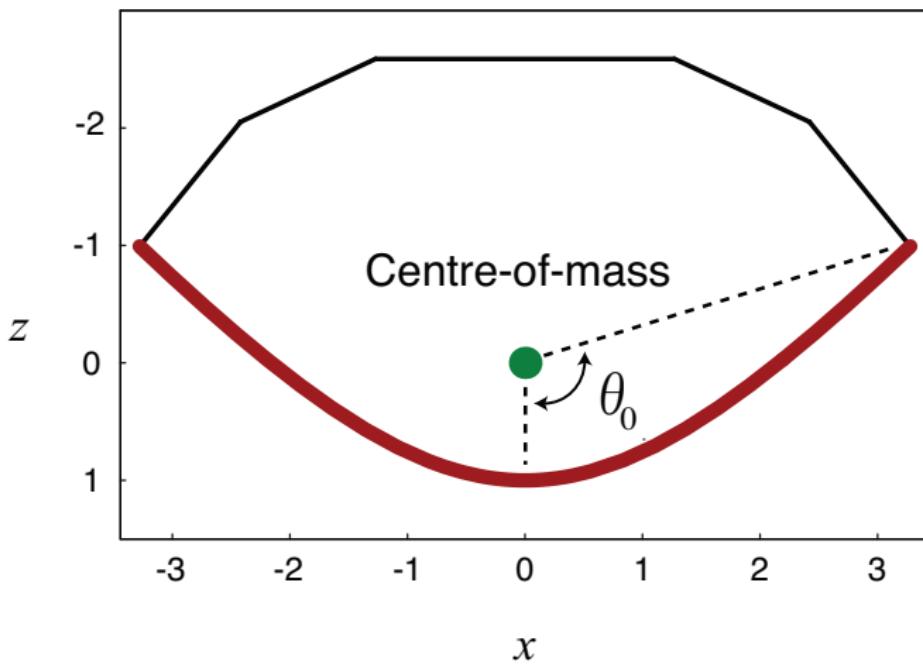
Heatshield



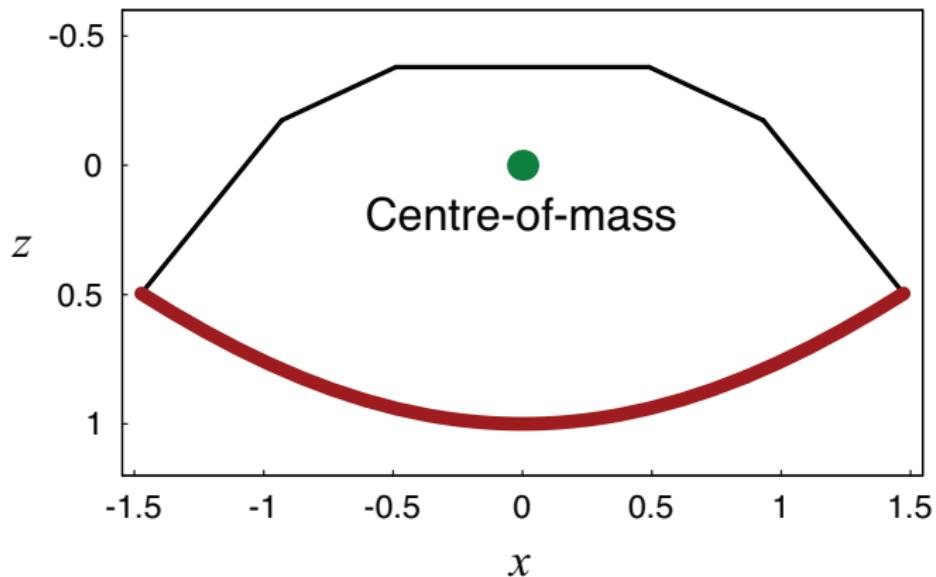
Torque integral (continuum)



Sample Entry Vehicles



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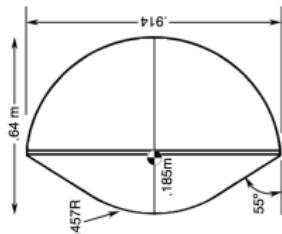


Comparison to Atmospheric Entry Vehicles

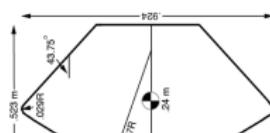
C. Davies

Planetary Mission Entry Vehicles
Quick Reference Guide, Version 3.0
NASA/SP-2006-3401

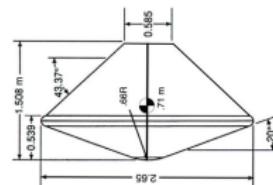
Comparison to Atmospheric Entry Vehicles



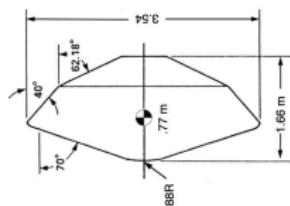
PAET
Earth, 1971



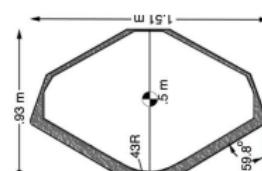
Beagle2
Mars, 2003



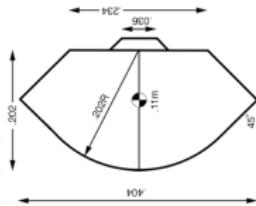
Mars Rovers
Mars, 2004



Viking
Mars, 1975

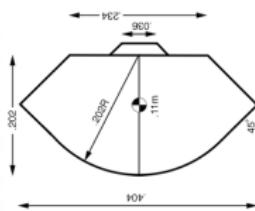
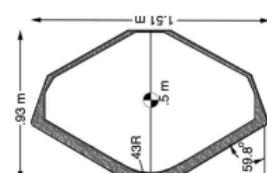
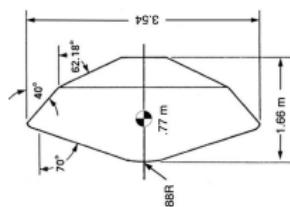
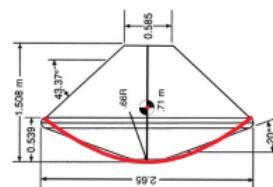
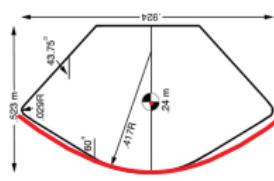
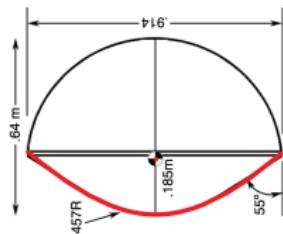


Genesis
Earth, 2004

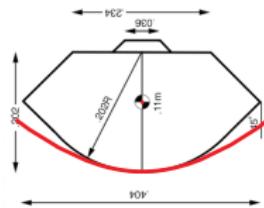
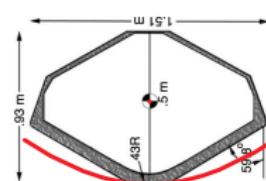
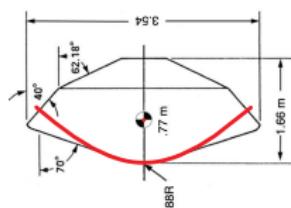
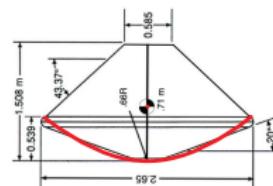
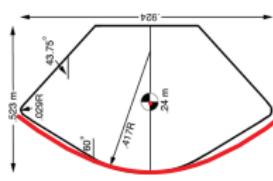
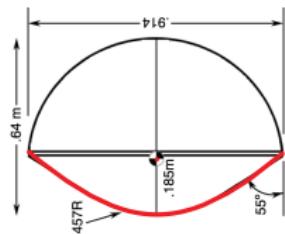


MUSES-C
Earth, 2007

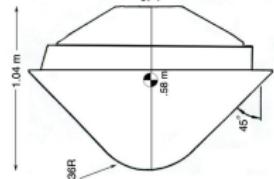
Comparison to Atmospheric Entry Vehicles



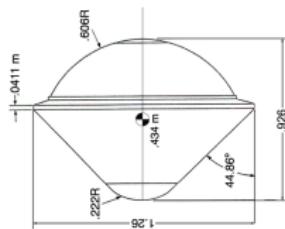
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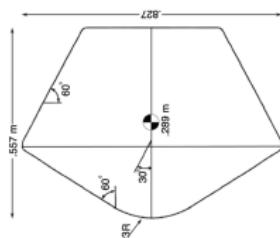
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Pioneer
Venus, 1978

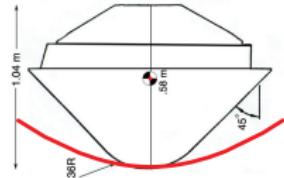


Galileo
Jupiter, 1995

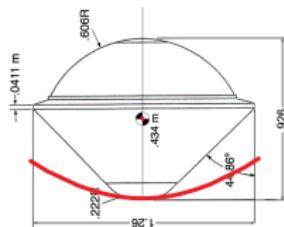


Stardust
Comet Wild 2/Earth, 2006

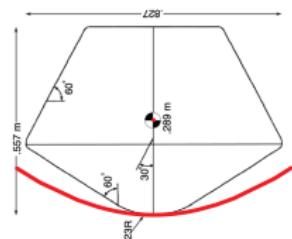
Comparison to Atmospheric Entry Vehicles



Pioneer
Venus, 1978



Galileo
Jupiter, 1995



Stardust
Comet Wild 2/Earth, 2006

Conclusions

- ▶ Generic sphere-cone shape can be derived mathematically
- ▶ Torque invariance for small perturbations
- ▶ Maximally stable torque, giving maximum static stability
- ▶ Applicable in continuum and FM flows

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AIAA Journal, 47, 1784-1787 (2009).